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Efficient Predictions of Wave-Induced Ship Motions for Ship Defence Models

Kevin McTaggart

Defence R&D Canada – Atlantic

Technical Memorandum

DRDC Atlantic TM 2004-041

February 2004

Canada

105-04557/

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Abstract

This report presents a library of wave-induced ship motion modules for use in simulation applications. The library is intended for ship defence models and other simulation applications requiring robustness, fidelity, and high computational speed. Ship motions in long-crested random seaways are determined using ship motion response amplitude operators (RAOs) computed by DRDC Atlantic's SHIPMO7 program. The output ship motions are given as perturbations relative to the steady or slowly varying input ship course. Time domain predictions from the library have been verified through comparisons with frequency domain predictions from SHIPMO7, which has undergone extensive validation. The library is available as a Python module and also as a dynamically linked library (DLL) callable from C++ and other compiled languages. During benchmarking on a 800 MHz Pentium III computer, ship motion predictions required approximately 0.002 s per time step, giving performance 50 times faster than real time for a typical simulation application using a time step size of 0.1 s.

Résumé

Ce rapport présente une bibliothèque de modules de simulation des mouvements des navires induits par des vagues. Cette bibliothèque a été conçue pour, notamment, des applications de simulation de la défense des navires qui exigent robustesse, fidélité et une grande rapidité de calcul. Les mouvements des navires dans une mer à vagues aléatoires de grande amplitude sont déterminés au moyen d'opérateurs d'amplitude de réaction des mouvements du navire (RAO pour response amplitude operators) calculés au moyen du programme SHIPMO7 de RDDC Atlantique. Les mouvements du navire produits par ce programme sont exprimés sous la forme d'écarts par rapport à la route initiale, qui est constante ou varie lentement. Les prévisions dans le domaine temporel obtenues au moyen de la bibliothèque ont été vérifiées en effectuant des comparaisons avec des prévisions dans le domaine des fréquences établies avec SHIPMO7, qui a été soumis à un programme de validation complet. Cette bibliothèque est disponible sous la forme d'un module Python, et également sous la forme d'une DLL (dynamically linked library ou bibliothèque de liens dynamiques), qui peut être appelée depuis C++ et d'autres langages compilés. Lors des essais effectués sur un ordinateur Pentium III cadencé à 800 MHz, les prévisions des mouvements du navire ont nécessité environ 0,002 s par accroissement de temps, ce qui est 50 fois plus rapide que les prévisions obtenues en temps réel avec une application de simulation typique fonctionnant avec un accroissement de temps de 0,1 s.

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Executive summary

Introduction

The Canadian Forces Maritime Warfare Centre tasked DRDC Atlantic with developing a library of wave-induced ship motion modules for use in simulation applications. Fidelity, robustness, and high computational speed were primary considerations when selecting a suitable approach.

Principal Results

Ship motions in long-crested random seaways are determined using ship motion response amplitude operators (RAOs) computed by DRDC Atlantic's SHIPMO7 program. The output ship motions are given as perturbations relative to a steady or slowly varying input ship course. Time domain predictions from the library have been verified through comparisons with frequency domain predictions from SHIPMO7, which has undergone extensive validation. During benchmarking on a 800 MHz Pentium III computer, ship motion predictions required approximately 0.002 s per time step, giving performance 50 times faster than real time for a typical simulation application using a time step size of 0.1 s.

Significance of Results

The library will bring enhanced fidelity to simulation applications for which ship motions influence system performance. Examples of entities influenced by ship motions include sensors, weapons, ship-borne aircraft, and humans. The fast computational speed of the ship motion predictions makes it practical to implement them into a variety of simulation applications.

Future Plans

DRDC Atlantic is developing a new ship motion library based on three-dimensional theory. The new library will give enhanced fidelity for non-slender hull forms and large amplitude motions. The new library will also be able to simulate ship maneuvering in response to input rudder and propeller states.

Kevin McTaggart; 2004; Efficient Predictions of Wave-Induced Ship Motions for Ship Defence Models; DRDC Atlantic TM 2004-041; Defence R&D Canada – Atlantic.

Sommaire

Introduction

Le Centre de guerre navale des Forces canadiennes a confié à RDDC Atlantique la tâche de développer une bibliothèque de modules de simulation des mouvements des navires induits par des vagues. Dans le choix de la méthode, la fidélité, la robustesse ainsi qu'une grande rapidité de calcul constituaient des facteurs déterminants.

Résultats principaux

Les mouvements des navires dans une mer à vagues aléatoires de grande amplitude sont déterminés au moyen d'opérateurs d'amplitude de réaction des mouvements du navire (RAO pour response amplitude operators) calculés au moyen du programme SHIPMO7 de RDDC Atlantique. Les mouvements du navire produits par ce programme sont exprimés sous la forme d'écarts par rapport à la route initiale, qui est constante ou varie lentement. Les prévisions dans le domaine temporel obtenues au moyen de la bibliothèque ont été vérifiées en effectuant des comparaisons avec des prévisions dans le domaine des fréquences établies avec SHIPMO7, qui a été soumis à un programme de validation complet. Lors des essais effectués sur un ordinateur Pentium III cadencé à 800 MHz, les prévisions des mouvements du navire ont nécessité environ 0,002 s par accroissement de temps, ce qui est 50 fois plus rapide que les prévisions obtenues en temps réel avec une application de simulation typique fonctionnant avec un accroissement de temps de 0,1 s.

Importance des résultats

Cette bibliothèque va améliorer la fidélité des applications de simulation dans lesquelles les mouvements des navires influent sur les performances du système. Citons, à titre d'exemples d'entités influencées par les mouvements des navires, les capteurs, les armes, les aéronefs embarqués et les humains. Grâce à la très grande rapidité d'établissement des prévisions concernant les mouvements du navire, il devient possible en pratique de s'en servir dans toute une variété d'applications de simulation.

Travaux ultérieurs prévus

RDDC Atlantique est en train de développer une nouvelle bibliothèque de simulations des mouvements des navires, basée sur la théorie tridimensionnelle. Cette nouvelle bibliothèque va améliorer la fidélité des simulations dans le cas des vagues de grande amplitude.

Kevin McTaggart; 2004; Efficient Predictions of Wave-Induced Ship Motions for Ship Defence Models; DRDC Atlantic TM 2004-041; Defence R&D Canada – Atlantic.

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1 Introduction

Modelling and simulation are widely used for a variety of military applications. For systems onboard ships, such as weapons and sensors, wave-induced ship motions often influence system effectiveness; thus, ship motions should be included when modelling ship systems. The Canadian Forces Maritime Warfare Centre tasked DRDC Atlantic with developing a library for incorporating ship motions into ship defence models.

When developing a suitable approach for modelling ship motions, the main considerations were robustness, fidelity, and computational speed. The selected approach provides ship motions in long-crested random seaways based on response amplitude operators (RAOs) previously computed using DRDC Atlantic's SHIPMO7 program [1]. SHIPMO7 computes ship motions in the frequency domain using strip theory, which assumes slender hull geometry. Extensive validation of SHIPMO7 [2, 3, 4, 5] has shown very good agreement with model tests and sea trials for frigates and destroyers. Good results can generally be expected from SHIPMO7 within the limitations of strip theory. Noticeable deterioration of motion predictions can occur for non-slender hull forms (e.g., length/beam < 6) or at higher ship speeds (e.g., Froude numbers > 0.4). The present approach assumes linear ship motion response, which gives good results for frigates in seaways up to NATO sea state 7.

Section 2 of this report presents coordinate systems used for computations. Section 3 describes the modelling of long-crested random seaways, followed by Section 4 describing the modelling of ship motions in those seaways. Section 5 presents the software implementation of the model. SHIPMO7 predictions of response amplitude operators have been performed for three ships representative of a corvette, frigate, and supply ship, as described in Section 6. Time domain predictions have been verified with frequency domain predictions from SHIPMO7, as shown in Section 7. The main report finishes with conclusions in Section 8. The appendices at the end of the report are intended for library users interested in importing their own ship motion RAOs.

2 Coordinate Systems

The coordinate systems for the present library were selected based on requirements from the Canadian Forces Maritime Warfare Centre. Figure 1 shows the earth-fixed coordinate system. The x_f axes is positive north and the y_f axis is positive east. Although not shown in Figure 1, the z_f axis has its origin at the mean still water level and is positive down. The ship heading χ is the direction to which the ship is going, with $\chi = 0$ degrees indicating that the ship is heading north. Similarly,

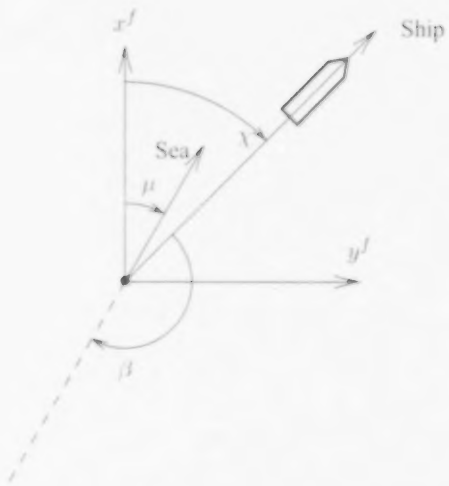

Figure 1: *Fixed Coordinate System*

the wave direction μ is the direction to which the waves are propagating, with $\mu = 0$ degrees indicating that the waves are heading north. For a ship travelling with steady speed and course, the nominal ship position (not including perturbations due to wave-induced motions) will be as follows:

$$x^f(t) = x^f(t_0) + (t - t_0)\ U\ \cos\ \chi \quad (1)$$

$$y^f(t) = y^f(t_0) + (t - t_0)\ U\ \sin\ \chi \quad (2)$$

where U is the steady ship speed.

Wave-induced ship motions are computed as perturbations relative to a steady or slowly varying ship course. The wave-induced ship motions are computed using a translating earth coordinate system (Figure 2) that moves with the nominal ship course. Wave-induced ship motions are computed for all six degrees of freedom.

As mentioned earlier, wave-induced ship motions are evaluated using RAOs previously computed by the frequency domain program SHIPMO7. RAOs for each motion mode are functions of ship speed U, relative sea direction β, and incident wave frequency ω_I. Figure 3 shows the definition of relative sea direction, which is related to ship heading and wave heading as follows:

$$\beta = \mu - \chi \quad (3)$$

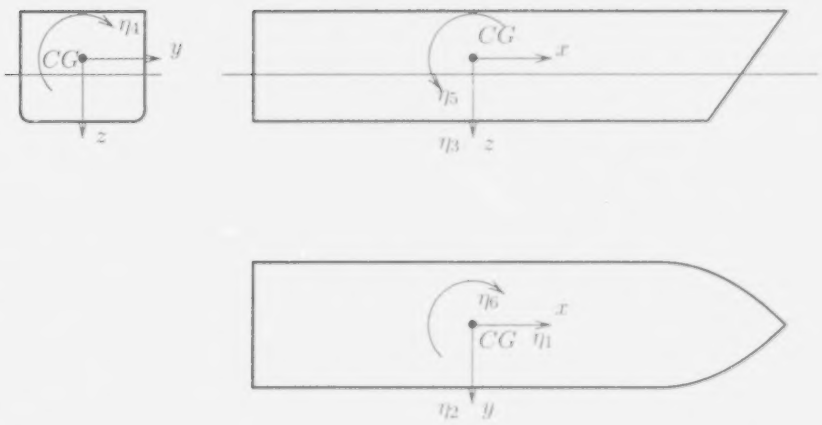

Figure 2: *Translating Earth Coordinate System*

Due to symmetry, ship motion RAOs only need to be stored for relative sea directions of 0 to 180 degrees.

3 Modelling of Long Crested Random Seaways

The modelling of seaways influencing ship motions is discussed in detail in Reference 6. The present work uses the coordinate system presented in the previous section.

The surface elevation of a regular seaway can be modelled as follows:

$$\zeta_I(x^f, y^f, t) \;=\; a\,\cos\Big[\,k_I\,\left(x^f\cos\nu \;+\; y^f\sin\mu\right) - \omega_I\,t - \epsilon_I^f\Big] \qquad (4)$$

where a is the wave amplitude, k_I is the incident wavenumber, x_f and y_f are the horizontal plane coordinates, ω_I is the incident wave frequency, and ϵ_I^f is the phase lead angle for the wave trough at the origin. The surface elevation uses the same sign convention as the z^f axis, with downward being positive. The present work assumes deep water (i.e., water depth greater than half of incident wavelength), and the following dispersion relation applies:

$$k_I \;=\; \frac{\omega_I^2}{g} \qquad (5)$$

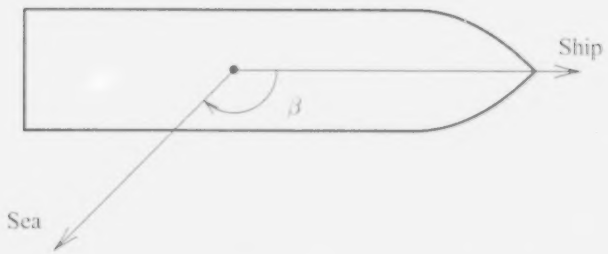

Figure 3: *Sea Direction Relative to Forward Ship Speed*

where g is gravitational acceleration.

A random seaway can be simulated by linear superposition of a finite number of regular wave components. Chakrabarti [7] provides a useful overview of this approach. Using the fixed axis systems of Figure 1, the z_f value of the free surface for a unidirectional random seaway can be simulated as follows:

$$\zeta_I(x^f, y^f, t) = \sum_{i=1}^{N_I} a_i \cos\left[k_{I-i} \left(x^f \cos\nu + y^f \sin\nu\right) - \omega_{I-i}\, t - \epsilon^f_{I-i}\right] \quad (6)$$

where N_I is the number of regular wave components used to represent the random seaway, a_i is the wave amplitude for component i, k_{I-i} is the wavenumber for component i, ω_{I-i} is the incident wave frequency for component i, and ϵ^f_{I-i} is the phase for wave component i. The wave amplitude for component i is based on a specified wave spectrum as follows:

$$a_i = \sqrt{2\, S_{\omega_I}(\omega_{I-i})\ \Delta(\omega_{I-i})} \quad (7)$$

where S_{ω_I} is the spectral density and $\Delta(\omega_{I-i})$ is the wave frequency interval for component i. The wave phase components ϵ^f_{I-i} are obtained using random number generation based on a uniform distribution between 0 and 2π. The following relationship exists between the the wave component amplitudes and the standard deviation of water elevation:

$$\sigma^2(\zeta) = \frac{1}{2} \sum_{i=1}^{N_I} a_i^2 \quad (8)$$

The fidelity of the simulated seaway will increase with number of wave components. A minimum of 19 components is typically used for simulating unidirectional random seaways.

Reference 6 describes several commonly used wave spectral models. The Bretschneider spectrum is the most widely used spectrum for waves in the open ocean, and has been selected for the present application. Based on the 15th International Towing Tank Conference (ITTC) [8], the formulation for the Bretschneider spectrum is:

$$S_{\omega_I}(\omega_I) = \frac{486.0\, H_s^2}{T_p^4\, \omega^5} \exp\left[\frac{-1948.2}{T_p^4\, \omega_I^4}\right] \tag{9}$$

The above spectrum is defined in terms of peak wave period T_p, which is associated with the wave frequency at which $S_{\omega_I}(\omega_I)$ has its maximum. For a Bretschneider spectrum, the following relations exist between the peak wave period and the average and zero-crossing wave periods:

$$T_1 = 0.773\, T_p \tag{10}$$

$$T_z = 0.710\, T_p \tag{11}$$

The current model of ship motions in waves requires the user to select suitable values of significant wave height H_s and peak wave period T_p. Available wave climate data can provide useful guidance for selecting seaway parameters. Table 1 gives NATO sea state numbers from Lee and Bales [9] and associated wave and wind parameters.

Table 1: *Sea State Parameters for the North Atlantic (reproduced from Reference 9)*

Sea State Number	Significant Wave Height (m)		Sustained Wind Speed (knots)		Percentage Probability of Seastate	Peak Wave Period	
	Range	Mean	Range	Mean		Range	Most Probable
0 - 1	0 - 0.1	0.05	0 - 6	3	0.7	-	-
2	0.1 - 0.5	0.3	7 - 10	8.5	6.8	3.3 - 12.8	7.5
3	0.5 - 1.25	0.88	11 - 16	13.5	23.7	5.0 - 14.8	7.5
4	1.25 - 2.5	1.88	17 - 21	19	27.8	6.1 - 15.2	8.8
5	2.5 - 4	3.25	22 - 27	24.5	20.6	8.3 - 15.5	9.7
6	4 - 6	5	28 - 47	37.5	13.1	9.8 - 16.2	12.4
7	6 - 9	7.5	48 - 55	51.5	6.1	11.8 - 18.5	15.0
8	9 - 14	11.5	56 - 63	59.5	1.1	14.2 - 18.6	16.4
> 8	> 14	> 14	> 63	> 63	0.05	18.0 - 23.7	20.0

When specifying input values for significant wave height and peak wave period, it is important that the resulting seaway have realistic wave steepnesses. Analysis of observed wave data by Buckley [10] indicates that the following condition should be

met when selecting input values for significant wave height and peak wave period:

$$\frac{H_s}{T_p^2\, g/(2\,\pi)} \;<\; 0.049 \tag{12}$$

The left hand side of the above equation represents a nominal wave steepness, with the denominator representing the wavelength in deep water associated with the peak wave period T_p. The existence of steeper waves is restricted by the occurrence of wave breaking.

4 Modelling of Ship Motions in Long Crested Random Seaways

When computing ship motions for use in ship defence models, it is important that computations can proceed much faster than real time for the following reasons:

- ship defence models consist of many different elements which must share computational resources,
- multiple runs of scenarios are often required for Monte Carlo simulation,
- many different scenarios are often examined to determine optimal tactics.

To achieve a suitable balance of fidelity and computational speed, ship motions in the time domain can be evaluated based on motion response amplitude operators (RAOs) previously computed in the frequency domain. For the present application, DRDC Atlantic's SHIPMO7 program [1] can be used to determine frequency domain RAOs. Comparisons with model tests [4] and full scale trials [5] indicate that SHIPMO7 gives very good predictions for naval frigates operating in seas with significant wave heights up to 7 m.

SHIPMO7 produces complex response amplitude operators of wave-induced motions for a ship travelling with steady speed and heading. For a ship in a sinusoidal seaway, the relationship between ship motions in the time and frequency domains can be expressed by:

$$\eta_j(t) \;=\; \text{Real}\left\{a\,\eta_j^*(U,\beta,\omega_I)\,\exp(i\,\omega_e\,t)\right\} \text{ for } j = 1-6 \tag{13}$$

where η_j is the displacement for mode j, Real$\{\ldots\}$ denotes the real part of the complex term in brackets, and η_j^* is the complex motion RAO (i.e., the complex motion amplitude in unit amplitude waves) for mode j. Assuming linear motion

response, the complex motion RAO is a function of ship speed U, relative sea direction β, and incident wave frequency ω_I. The wave encounter frequency ω_e for the ship travelling at steady speed and heading is given by:

$$\omega_e = |\omega_I - U\, k_I \cos\beta| \tag{14}$$

Although Equation (13) assumes linear motion response, roll response is actually nonlinear due to the importance of nonlinear viscous roll damping. To account for this effect, ship motion RAOs can be computed for a specified nominal seaway. For frequency domain computations, an iterative procedure is typically used to obtain the correct roll amplitude in a specified seaway.

When solving for ship motions in the frequency domain, computations are performed in translating earth axes which travel at the steady speed and heading of the ship. In the present coordinate system, it is specified that the wave trough will be located at $x = 0, y = 0$ (see Figure 2) at time $t = 0$. The resulting motions in the time domain will be related to the predicted frequency domain motions as follows:

$$\eta_j(t) = a\ \left|\eta_j^*(U,\beta,\omega_I)\right|\ \cos\left[\omega_e\, t\ + \epsilon_j(U,\beta,\omega_I)\right] \text{ for } j = 1-6 \tag{15}$$

The phase lead of the motions relative to the wave trough being at the origin is given by:

$$\epsilon_j(U,\beta,\omega_I) = \arctan\frac{\text{Imag}\left\{\eta_j^*(U,\beta,\omega_I)\right\}}{\text{Real}\left\{\eta_j^*(U,\beta,\omega_I)\right\}} \tag{16}$$

where Imag $\{\ldots\}$ denotes the imaginary part of the complex term in brackets.

When computing ship motions within ship defence models, it is essential to account for the possibility of ship speed and/or heading changing with time, as can occur while a ship maneuvers. For a ship in a fixed seaway modelled using Equation (4), the instantaneous ship motions can be expressed as:

$$\eta_j(t) = \sum_{i=1}^{N_I} a_i\ \left|\eta_j^*(U,\beta,\omega_I)\right| \cos\left[\omega_{e-i}(U,\beta,\omega_{I-i})\, t + \epsilon_{I-i} + \epsilon_j\right] \tag{17}$$

where ϵ_{I-i} is the phase lead angle of the incident wave trough of wave component i in translating earth axes with their origin at the ship centre of gravity. The wave elevation in translating earth axes from wave component i is given by:

$$\zeta_{I-i}(x,y,t) = a_i\, \cos\left[k_{I-i}\,(x\cos\beta\ +\ y\sin\beta)\ -\ \omega_{e-i}\, t\ -\ \epsilon_{I-i}\right] \tag{18}$$

Based on Equations (6) and (18), the wave elevation phase in translating earth coordinates at any time during a simulation is given by:

$$\epsilon_{I-i} = \epsilon_{I-i}^f + t\ (\omega_{I-i} - \omega_{e-i}) - k_{I-i}\ (x^f\cos\mu\ +\ y^f\sin\mu) \tag{19}$$

When applying the above equation, x^f are y^f are the instantaneous coordinates of the ship centre of gravity. If both the ship speed and heading remain constant during a simulation, then the wave elevation phase term ϵ_{I-i} will also remain constant.

Wave-induced ship velocities and accelerations are often required during simulations. These terms can be obtained from differentiation of Equation (17):

$$\dot{\eta}_j(t) = \sum_{i=1}^{N_I} -\omega_{e-i}\, a_i\, \left|\eta_j^*(U,\beta,\omega_I)\right| \sin\left[\omega_{e-i}(U,\beta,\omega_{I-i})t + \epsilon_{I-i} + \epsilon_j\right] \quad (20)$$

$$\ddot{\eta}_j(t) = \sum_{i=1}^{N_I} -\omega_{e-i}^2\, a_i\, \left|\eta_j^*(U,\beta,\omega_I)\right| \cos\left[\omega_{e-i}(U,\beta,\omega_{I-i})t + \epsilon_{I-i} + \epsilon_j\right] \quad (21)$$

The equations presented thus far give the motions at the ship centre of gravity. Local motions at a ship location offset from the centre of gravity are often of interest. For a location on a ship specified using the translating earth coordinates of Figure 2, the local motions in translating earth coordinates are given as follows:

$$\xi_1(t) = \eta_1(t) + z\,\eta_5(t) - y\,\eta_6(t) \quad (22)$$

$$\xi_2(t) = \eta_2(t) - z\,\eta_4(t) + x\,\eta_6(t) \quad (23)$$

$$\xi_3(t) = \eta_3(t) + y\,\eta_4(t) - x\,\eta_5(t) \quad (24)$$

The above equations are based on the assumption of small angular motions.

5 Software Implementation

A module has been developed using the computer language Python [11, 12] to provide ship motions for ship defence simulations. Python is an open source programming language that has a wide user base, including many scientific users. Python is object-oriented like C++ and Java; however, it is a higher level language, which results in significantly fewer lines of code being required to develop a specific application. The availability of the Numeric library [13] has been a primary reason for Python's acceptance among scientific users. Python has been used since 2001 for development of ship motion predictions at DRDC Atlantic [6, 14, 15].

For the present application, ship motion RAOs are computed using DRDC Atlantic's SHIPMO7 [1]. SHIPMO7 is based on strip theory, which models the geometry of a hull using a number of two-dimensional sections (typically 21) along the hull length. Strip theory is based on the assumptions of slender hull geometry and moderate ship speed. Comparisons with experiments and full-scale trials [2, 4, 5, 16] indicate that SHIPMO7 gives very good results for ships with

length/beam ratios greater than 6 travelling at Froude numbers less than 0.4 (27 knots for a frigate with waterline length of 120 m).

A Python class *ShipMotionDefenceRAODBSeaway* has been developed to provide ship motions for ship defence models. An instance of this class is initialized with the following input variables:

- fileNameSm7RAO — file name of SHIPMO7 ASCII post-processing file with motion RAOs,
- hSig — significant wave height (m),
- tPeak — peak wave period (s),
- waveHeadingToDeg — direction (deg) to which waves are heading (0 degrees for waves heading north, 90 degrees for waves heading east),
- waveFreqs — sequence of wave frequencies (rad/s). If these are not given as input, then default values of 0.2, 0.3, . . ., 2.0 rad/s are used.
- wavePhaseSeeds — sequence of two integer seed numbers for generation of phases for seaway components. If these are not given as input, then default values of 1001 and 7001 are used.

In the above variable descriptions, the term "sequence" indicates a collection of values which can be in the form of a Python list, tuple, or Numeric array.

Annex A gives the format of the SHIPMO7 post-processing file. When preparing a SHIPMO7 post-processing file to be used for ship motion simulations, attention must be given to selecting suitable ranges of ship speeds, relative sea directions, and wave frequencies. The SHIPMO7 computations must encompass the range of ship speeds that will be required for motion simulations. It is recommended that a ship speed interval of 5 knots or smaller be used. SHIPMO7 relative sea directions must have a minimum value of 0 degrees, a maximum value of 180 degrees, and a direction interval no greater than 30 degrees. It is recommend that wave frequencies of 0.2, 0.3, . . ., 2.0 rad/s be used. If a simulation requires motions at lower frequencies than are available in the SHIPMO7 file, then approximations are made based on the lowest frequency for which SHIPMO7 computations are available. If a simulation requires motions at higher frequencies than are available in the SHIPMO7 file, then ship motions are assumed to be zero.

During initialization of a *ShipMotionDefenceRAODBSeaway* object, the ship motion RAOs are converted from the SHIPMO7 axis system of Reference 1 to that given in Figure 2. The conversion process must account for the convention in the present work that motion phases are relative to when a wave trough passes the

Table 2: *Multiplication Factors for Obtaining Complex Ship Motion RAOs from SHIPMO7 RAOs*

Surge	-1
Sway	$+1$
Heave	$+1$
Roll	-1
Pitch	$+1$
Yaw	$+1$

ship CG, with conversion factors given in Table 2. Motions RAOs are ultimately stored at the wave frequencies for the simulated seaway. Linear interpolation is used when wave frequencies from the SHIPMO7 RAOs differ from those for the simulated seaway.

Once the *ShipMotionDefenceRAODBSeaway* object has been initialized, motion displacements at the ship centre of gravity at a given instant in time can be obtained using the method *displacementsCG*, which has the following input variables:

- t — time (s),
- speed — ship speed at time t (m/s),
- shipHeadingToDeg — ship heading (deg) (0 degrees for ship heading north, 90 degrees for ship heading east),
- xf — x coordinate of ship CG in fixed coordinate system,
- yf — y coordinate of ship CG in fixed coordinate system,

Method *displacementsCG* returns the following wave-induced motion components in the translating axis system of Figure 2:

- surge (m),
- sway (m),
- heave (m),
- roll (deg),
- pitch (deg),
- yaw (deg).

Note that the above motion displacements are relative to the intended ship course in calm water. Methods *velocitiesCG* and *accelerationsCG* are also available for obtaining wave-induced ship velocities and accelerations. Velocities have units of m/s and deg/s, and accelerations have units of m/s^2 and deg/s^2.

Benchmark tests have been performed on a 800 MHz Pentium III computer to determine computational requirements for modelling ship motions. Each call to method *displacementsCG* requires approximately 0.002 s of CPU time. For a representative simulation computing ship motions at a time interval of 0.1 s, the ship motion predictions would run approximately 50 times faster than real time.

To facilitate usage by programs written in C++, the Python class *ShipMotionDefenceRAODBSeaway* has been implemented as a C++ class in a dynamically linked library (DLL). The DLL interface is given in the C++ header file *DRDCShipMotionDefence.h*, and an example C++ program *testShipMotionDefence.exe* demonstrates usage. Execution of the *ShipMotionDefenceRAODBSeaway* DLL and test program requires that the files *boost_python.dll*, *DRDCPythonWrapper.dll*, and *stlport_vc646.dll* be available in the current path at runtime.

6 Sample Ships for Pre-Computed Ship Motion RAOs

To facilitate integration of ship motions into ship defence models, files with motion RAOs have been prepared using SHIPMO7 for three sample ships of different sizes with properties given in Table 3. The three ships are geosims, with the 120 m frigate being the parent ship geometry, and the 70 m corvette and the 200 m supply ship being scaled from the frigate dimensions. The hull geometry is taken from Reference 17, and is representative of modern frigates, which have wide transom sterns. Figure 4 shows the hull lines and waterline. Each sample ship has bilge keels, a skeg, and a single rudder. Appendage dimensions were chosen to be representative of modern naval vessels. The height of the center of gravity for each ship is also representative of modern naval vessels, and is primarily influenced by requirements of stability standards for prevention of ship capsize. In summary, the hull forms, appendages, and inertial properties of the sample ships are representative of operational naval vessels, and the resulting motions in waves can be expected to be realistic. Annex B gives the SHIPMO7 input file for the sample frigate.

The computed ship motion RAOs for the sample ships cover the following parameter ranges:

- ship speeds U of 0, 5, 10, . . ., 30 knots,

Table 3: *Properties of Sample Ships*

	Corvette	Frigate	Supply Ship
Length between perpendiculars L (m)	70.0	120.0	200.0
Beam B (m)	8.228	14.106	23.513
Draft at midships T_{mid} (m)	2.450	4.200	7.0
Trim by stern t_s (m)	0.000	0.000	0.000
Displacement $\triangle$ (tonnes)	741	3735	17295
Height of CG above waterline (m)	1.050	1.800	3.0
Metacentric height $\overline{GM}$ (m)	0.815	1.398	2.334
Roll radius of gyration (m)	2.800	4.800	8.000
Pitch radius of gyration (m)	17.5	30.0	50.0
Yaw radius of gyration (m)	17.5	30.0	50.0
Natural roll period (s)	7.1	9.1	11.7

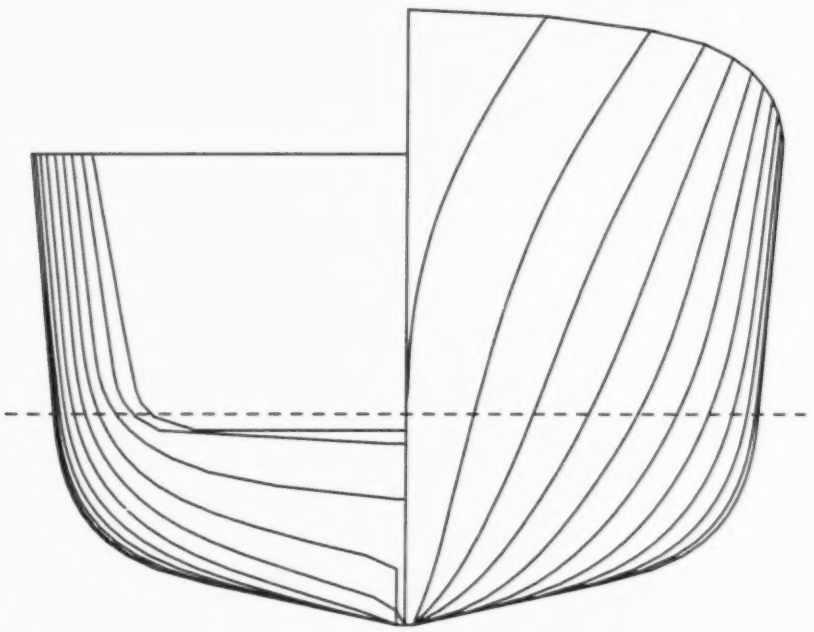

Figure 4: *Hull Lines for Sample Ships*

- relative sea directions β of 0, 15, 30, ..., 180 degrees,
- incident wave frequencies ω_I of 0.2, 0.3, 0.4, ..., 2.0 rad/s.

The ship speeds are considered to cover a realistic range of values. The relative sea directions were selected such that all relative headings are covered due to the assumption of lateral ship symmetry. The incident wave frequencies encompass all relevant frequencies at which significant energy can occur to influence ship motions.

7 Verification with Frequency Domain Motion Computations

As indicated previously, the ship motion program SHIPMO7 has been validated extensively, including comparisons with model tests [2, 4] and full-scale trials [5]. These comparisons indicate that SHIPMO7 gives good agreement for slender hull forms travelling at moderate forward speed.

To verify the present library for ship motions in the time domain, comparisons of motions have been made with frequency domain predictions from SHIPMO7. Figures 5 and 6 show motions at the ship centre of gravity in NATO sea state 5, and indicate excellent agreement. To verify that the relative phasing of motion modes is correct, further computations have been performed for a point offset from the ship centre of gravity. The selected point is located at station 3 (stations 0 and 20 represent the forward and aft perpendiculars respectively), has a lateral offset of 5 m to port, and is 2 m above the ship baseline. The lateral and vertical displacements in Figures 7 and 8 show excellent agreement between the frequency and time domain predictions, indicating that phasing between motion modes is correct. To verify phasing between the simulated ship motions and seaway, relative motions (local vertical displacement minus local seaway elevation) have been computed for the offset location used for verifying lateral displacement. Figure 9 shows excellent agreement between the results from the frequency and time domains.

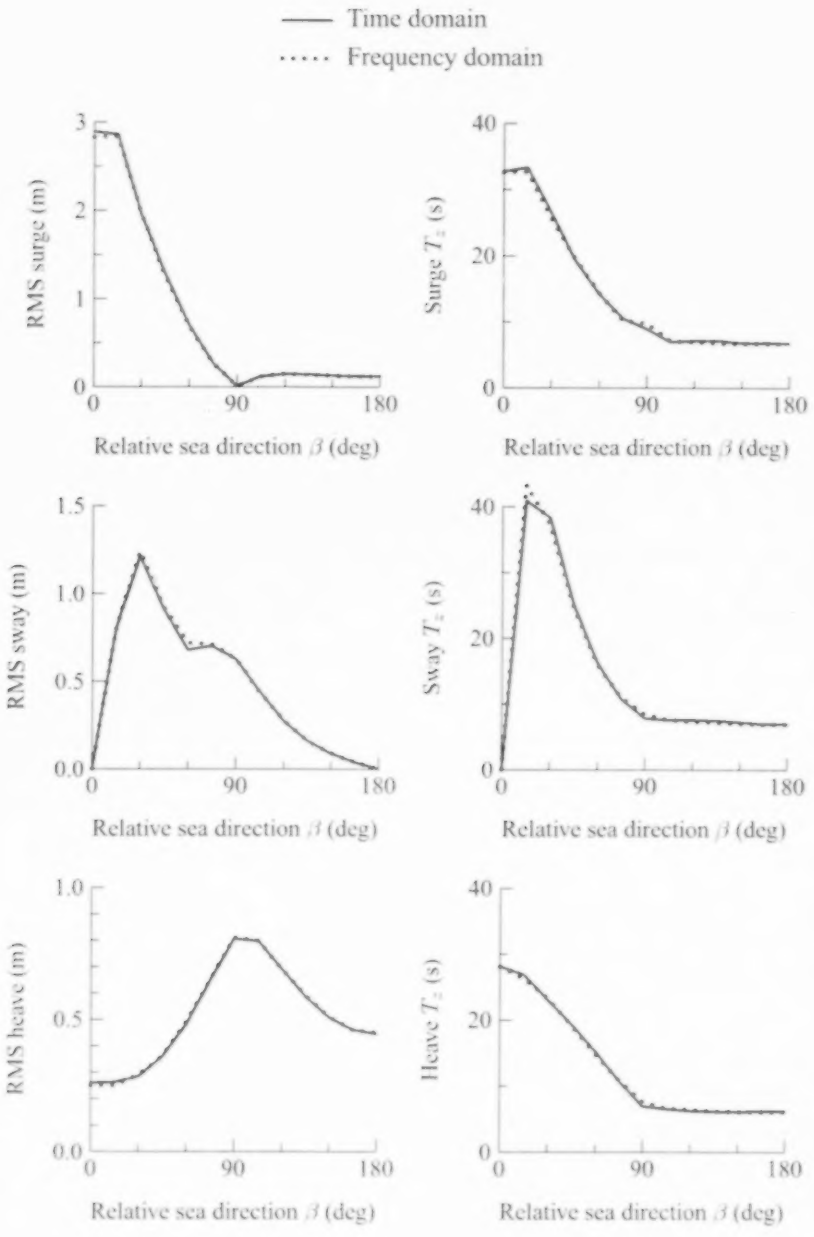

***Figure 5**: RMS Motions and Zero Crossing Periods for Frigate Surge, Sway, and Heave, H_s = 3.25 m, T_p = 9.7*

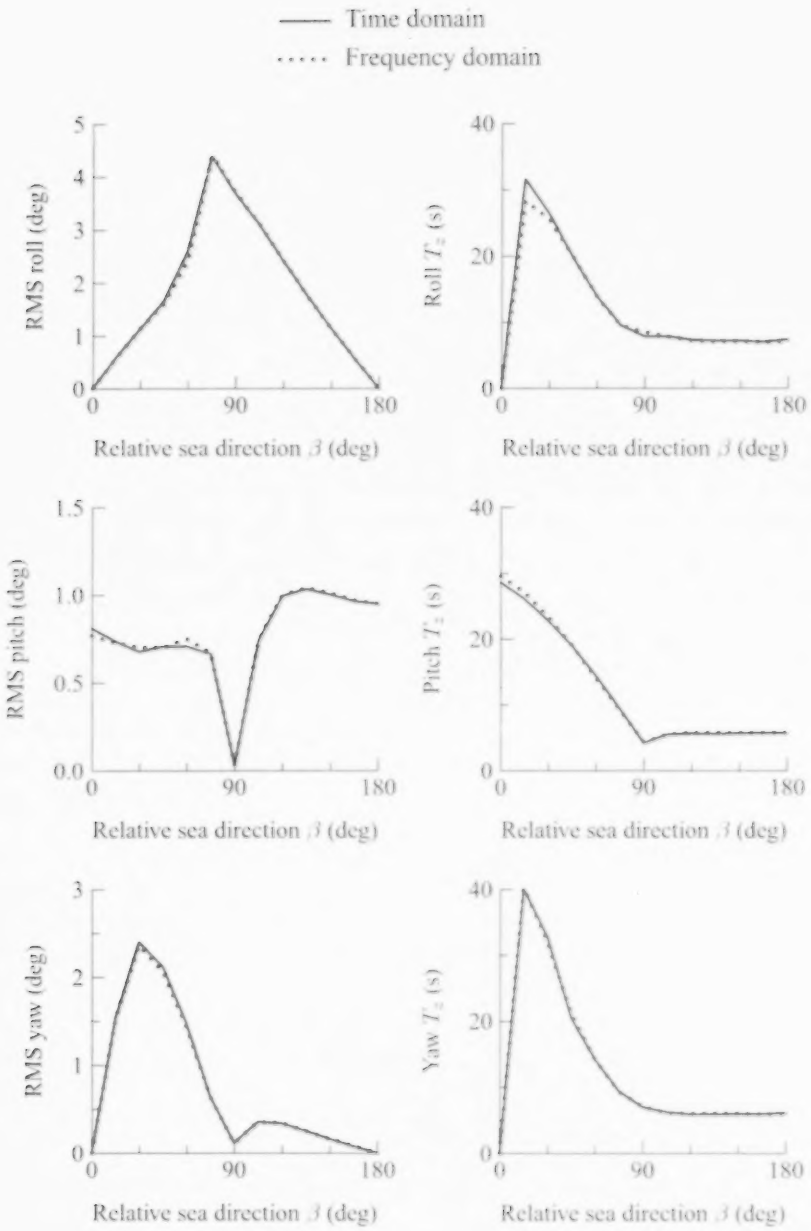

Figure 6: *RMS Motions and Zero Crossing Periods for Frigate Roll, Pitch, and Yaw, H_s = 3.25 m, T_p = 9.7*

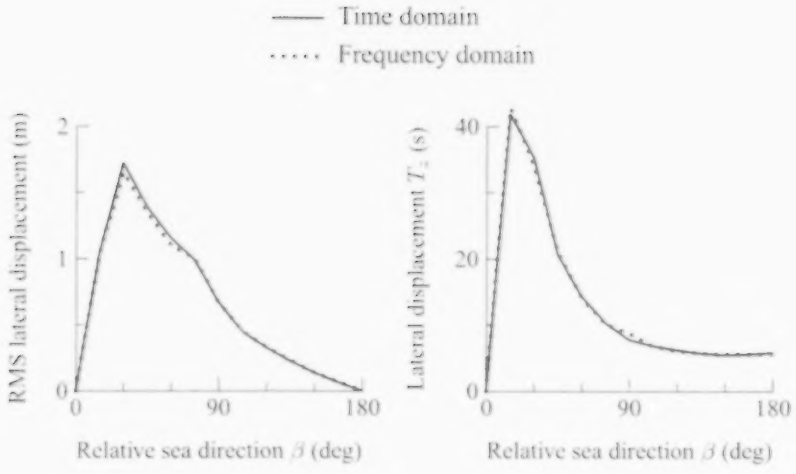

***Figure 7**: RMS Motions and Zero Crossing Periods for Lateral Displacement at Offset Point on Frigate, H_s = 3.25 m, T_p = 9.7*

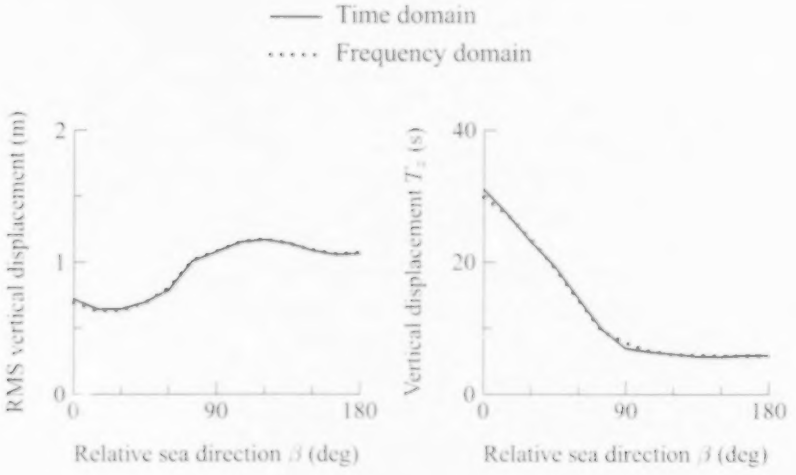

***Figure 8**: RMS Motions and Zero Crossing Periods for Vertical Displacement at Offset Point on Frigate, H_s = 3.25 m, T_p = 9.7*

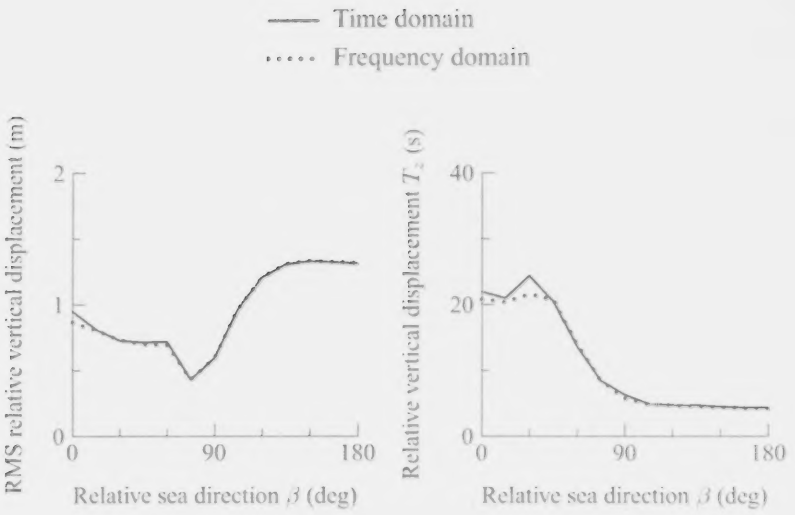

Figure 9: *RMS Motions and Zero Crossing Periods for Relative Vertical Displacement at Offset Point on Frigate, H_s = 3.25 m, T_p = 9.7*

8 Conclusions

A library has been developed for predicting wave-induced ship motions in long-crested seas. The library is suitable for ship defence models and other applications requiring a combination of good fidelity and high computational speed. Wave-induced motions are computed as perturbations from a prescribed ship trajectory.

Using a relatively slow desktop computer, computations of ship motions require approximately 0.002 s of CPU time per time step. For a typical simulation application with a step size of 0.1 s, the ship motion computations will run approximately 50 times faster than real time.

To facilitate usage of the library, ship motion RAOs are available for three representative ships with lengths of 70 m (nominal corvette), 120 m (nominal frigate), and 200 m (nominal supply ship).

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Symbols and Abbreviations

a	wave amplitude
a_i	amplitude of wave component i
B	beam
CG	centre of gravity
DLL	dynamically linked library
Fn	Froude number
$\overline{GM}$	metacentric height
g	gravitational acceleration
H_s	significant wave height
k_I	incident wavenumber
k_{I-i}	incident wavenumber of wave component i
L	ship length between perpendiculars
RMS	root-mean-square
$S_{\omega_I}(\omega_I)$	wave spectral density
T_{mid}	draft at midships
T_p	peak wave period
T_z	zero-crossing period of spectrum
T_1	average wave period
t_s	trim by stern
t_0	reference time
U	ship forward speed
x, y, z	coordinates in translating earth axes
x^f, y^f, z^f	coordinates in earth-fixed axes
β	wave direction relative to ship
$\Delta(\omega_{I-i})$	frequency increment of wave component i
ϵ_j	phase lead of motion RAO for mode j
ϵ_I	phase lead of incident wave in translating earth coordinate system
ϵ_I^f	phase lead of incident wave in fixed coordinate system
ϵ_{I-i}^f	phase lead of incident wave component i
ζ_I	incident z location of wave surface
η_j	motion displacement in mode j
η_j^*	complex motion RAO for mode j
μ	wave heading (to) in fixed coordinate system
ξ_j	local displacement in direction j
σ	standard deviation
χ	ship heading (toward) in fixed coordinate system
ω_I	incident wave frequency
ω_{I-i}	incident frequency of wave component i

ω_e	wave encounter frequency
ω_p	peak wave frequency

Annex A
ASCII Post-Processing Output File Format from SHIPMO7

The most recent version (7.3) of DREA's SHIPMO program [1] writes output post-processor files in ASCII rather than binary format. ASCII files are compatible across platforms and can be read by programs written in any computer language. SHIPMO version 7.3 uses Fortran 90 allocatable arrays, which greatly reduces the size of output post-processor files. For SHIPMO 7.3 to write an ASCII post-processor file, control variable OUTPPR of Record (b) of the SHIPMO input file must be set to OUTASCII.

Record 1 - Source Program Name
Format (A20)

PROGRAM Ch*20 Character string "SHIPMO7.3" identifying program name.

Record 2 - Title
Format (A100)

TITLE Ch*100 Run title with time and date appended.

Record 3 - Control Variables
Format (A20, 1X, A20, 1X, A20, 1X, A20)

OUTSYS Ch*20 Output units (BRITISH or METRIC).

WATERTYPE Ch*20 Water type (SALT or FRESH).

HYMETHOD Ch*20 Method for computing hydrodynamic coefficients (BOUND-2D or CONFORMAL).

SPECTRUM Ch*20 Spectrum type (REGULAR, QUADRATIC, BRETSCHNEIDER, JONSWAP, OCHIHUBBLE, INPUTUNI, TENPARAMETER, ODGPHINDCAST, or INPUTDIR)

Record 4 - Ship Dimensions
Format (F12.3, 1X, I4, 6(1X, F12.3))

SHIPLEN	Real	Ship length between perpendiculars (ft or m).
NST	Integer	Number of stations (typically 21).
DISP	Real	Ship displacement (tons or tonnes).
LCBFP	Real	Distance from forward perpendicular to LCB (ft or m).
DRAFTMID	Real	Draft at midships (ft or m).
TRIMST	Real	Trim by stern (ft or m).
KG	Real	Height of CG above baseline (ft or m).
BEAMMID	Real	Beam at midships (ft or m).

Record 5 - Physical Constants
Format (F12.3, 1X, F12.3)

WDENSITY	Real	Water density (slugs/ft^3 or kg/m^3).
GRAVITY	Real	Gravitational acceleration (ft/s^2 or m/s^2).

Record 6 - Number of Stations for Sea Load Computations
Format (I4)

NSTLOAD	Integer	Number of stations for sea load computations.

Record 7 - Stations for Sea Load Computations
Written only if NSTLOAD $\geq$ 1 in Record (6)
Format (10(F10.3, 1X))

XSTLOAD(I)	Real	Array of dimension NSTLOAD with station numbers for sea loads.

Record 8 - Number of Positions for Seakeeping Calculations
Format (I4)

NPOS	Integer	Number of positions for seakeeping computations.

Record 9 - Position Locations for Seakeeping Calculations
Written only if NPOS $\geq$ 1 in Record (8)
Format (9(F10.3, 1X))

XSTPOS(I)	Real	Array of dimension NPOS with station numbers of seakeeping positions.
YPOS(I)	Real	Array of dimension NPOS with horizontal coordinates of seakeeping positions (ft or m).
ZPOSBL(I)	Real	Array of dimension NPOS with vertical coordinates of seakeeping positions relative to baseline (ft or m).

Record 10 - Number of Ship Speeds
Format (I4)

NSPEED	Integer	Number of ship speeds.

Record 11 - Ship Speeds
Format (10(F10.3, 1X))

SPDKNOT(I)	Real	Array of dimension NSPEED with ship speeds (knots).

Record 12 - Number of Sea Directions
Format (I4)

NSEADIR	Integer	Number of sea directions.

Record 13 - Sea Directions
Format (10(F10.3, 1X))

SEADIR(I)	Real	Array of dimension NSEADIR with sea directions.

Record 14 - Number of Seaways
Format (I4)

NSEAWAY	Integer	Number of seaways.

Record 15 - Seaways
Format (10(F10.3, 1X))

HSW(I)	Real	Array of dimension NSEAWAY with significant wave heights (ft or m).
TSW(I)	Real	Array of dimension NSEAWAY with characteristic wave periods (s).

Record 16 - Wave frequencies
Format (I4, 1X, F9.3, 1X, F9.3)

NWVFREQ	Integer	Number of wave frequencies.
WVFREQMIN	Real	Minimum wave frequency (rad/s).
DWVFREQ	Real	Wave frequency increment (rad/s).

Ship Motions and Loads in Regular and Irregular Seas for each Ship Speed

The remaining sequence of records is repeated for each ship speed. For regular seas and irregular seas with a principal wave direction, the sea direction index J in the motion and load arrays corresponds to the sea direction relative to the ship forward speed. For irregular seas without a principal wave direction (SPECTRUM = TENPARAMETER, ODGPHINDCAST, or INPUTDIR), the direction index J corresponds to the ship compass heading for the irregular responses only.

Record 17 - Label for Ship Speed
Format (A40)

SPEEDLABEL	Ch*40	"Results for Following Ship Speed (knots)"

Record 18 - Ship Speed
Format (F9.3)

SPEEDKT Real Ship speed (knots)

Record 19 - Label for Complex Motion RAOs in Regular Waves
Format (A36)

MOTIONRAOLABEL Ch*36 "Complex Motion RAOs in Regular Waves"

Record 20 - Complex Motions in Unit Amplitude Regular Waves for Seaway 1
Format (5('(', E12.6, ',', E12.6, ')'))

CSURGEREG(I,J) Cmplx Complex surge amplitude (ft/ft or m/m).

CSWAYREG(I,J) Cmplx Complex sway amplitude (ft/ft or m/m).

CHEAVEREG(I,J) Cmplx Complex heave amplitude (ft/ft or m/m).

CROLLREG(I,J) Cmplx Complex roll amplitude (rad/ft or rad/m).

CPITCHREG(I,J) Cmplx Complex pitch amplitude (rad/ft or rad/m).

CYAWREG(I,J) Cmplx Complex yaw amplitude (rad/ft or rad/m).

CRUDREG(I,J) Cmplx Complex rudder amplitude (rad/ft or rad/m).

CSTABREG(I,J) Cmplx Complex fin or U-tube tank amplitude (rad/ft or rad/m).

Notes: The above arrays have dimensions (NWVFREQ, NSEADIR).

Regular wave motions and loads are given only for the first seaway regardless of the number of seaways.

Record 21 - Label for Complex Sea Loads in Regular Waves
Written only if NSTLOAD $\geq$ 1 in Record 6
Format (A38)

LOADRAOLABEL Ch*38 "Complex Sea Load RAOs in Regular Waves"

Record 22 - Complex Sea Loads in Unit Amplitude Regular Waves for Seaway 1

Written only if NSTLOAD geq 1 in Record 6
Format (5('(', E12.6, ',', E12.6, ')', 1X))

CHORSHRREG(I,J,K)	Cmplx	Complex horizontal shear amplitude (lb/ft or N /m).
CVERTSHRREG(I,J,K)	Cmplx	Complex vertical shear amplitude (lb/ft or N /m).
CTORSIONREG(I,J,K)	Cmplx	Complex torsional amplitude (lb-ft/ft or N-m/m).
CVERTBNDREG(I,J,K)	Cmplx	Complex vertical bending moment amplitude (lb-ft/ft or N-m/m).
CHORBNDREG(I,J,K)	Cmplx	Complex horizontal bending moment amplitude (lb-ft/ft or N-m/m).

Note: The above arrays have dimensions (NWVFREQ, NSEADIR, NST-LOAD).

Within the motions and loads written for each ship speed, the following sequence of RMS responses in irregular seas is repeated for each seaway if SPECTRUM is not equal to REGULAR.

Record 23 - Label for RMS Motions at CG in Irregular Waves
Format (A36)

RMSCGLABEL Ch*36 "RMS Motions at CG in Irregular Waves"

Record 24 - RMS Motions at Ship Centre of Gravity
Format (10(E12.6, 1X))

RMSSURGE(I)	Real	RMS surge (ft or m).
RMSSWAY(I)	Real	RMS sway (ft or m).
RMSHEAVE(I)	Real	RMS heave (ft or m).
RMSROLL(I)	Real	RMS roll (degrees).

RMSPITCH(I)	Real	RMS pitch (degrees).
RMSYAW(I)	Real	RMS yaw (degrees).
RMSRUD(I)	Real	RMS rudder deflection (degrees).
RMSSTAB(I)	Real	RMS stabilizer deflection (degrees).
RMSSURGEVEL(I)	Real	RMS surge velocity (ft/s or m/s).
RMSSWAYVEL(I)	Real	RMS sway velocity (ft/s or m/s).
RMSHEAVEVEL(I)	Real	RMS heave velocity (ft/s or m/s).
RMSROLLVEL(I)	Real	RMS roll velocity (deg/s).
RMSPITCHVEL(I)	Real	RMS pitch velocity (deg/s).
RMSYAWVEL(I)	Real	RMS yaw velocity (deg/s).
RMSRUDVEL(I)	Real	RMS rudder velocity (deg/s).
RMSSTABVEL(I)	Real	RMS stabilizer velocity (deg/s).
RMSSURGEACC(I)	Real	RMS surge acceleration (g).
RMSSWAYACC(I)	Real	RMS sway acceleration (g).
RMSHEAVEACC(I)	Real	RMS heave acceleration (g).
RMSROLLACC(I)	Real	RMS roll acceleration (deg/s^2).
RMSPITCHACC(I)	Real	RMS pitch acceleration (deg/s^2).
RMSYAWACC(I)	Real	RMS yaw acceleration (deg/s^2).
RMSRUDACC(I)	Real	RMS rudder acceleration (deg/s^2).
RMSSTABACC(I)	Real	RMS stabilizer acceleration (deg/s^2).

Note: The above arrays have dimension (NSEADIR).

Record 25 - Label for RMS Motions at Seakeeping Positions in Irregular Waves
Written only if NPOS $\geq$ 1 in Record (8)
Format (A54)

RMSPOSLABEL Ch*54 "RMS Motions at Seakeeping Positions in Irregular Waves"

Record 26 - RMS Motions at Seakeeping Positions

Written only if NPOS $\geq$ 1 in Record (8)

Format (10(E12.6, 1X))

RMSVERTDISP(I,J)	Real	RMS vertical displacement (ft or m).
RMSVERTVEL(I,J)	Real	RMS vertical velocity (ft/s or m/s).
RMSVERTACC(I,J)	Real	RMS vertical acceleration (g).
RMSRELDISP(I,J)	Real	RMS relative vertical displacement (ft or m).
RMSRELVEL(I,J)	Real	RMS relative vertical velocity (ft/s or m/s).
RMSLATDISP(I,J)	Real	RMS lateral displacement (ft or m).
RMSLATVEL(I,J)	Real	RMS lateral velocity (ft/s or m/s).
RMSLATACC(I,J)	Real	RMS lateral acceleration (g).
RMSLATFE(I,J)	Real	RMS lateral force estimator (g).
RMSGFEPORT(I,J)	Real	RMS force estimator function for tips or slides to port (g).
RMSGFEPORTVEL(I,J)	Real	RMS time derivative of port estimator (g/s).
RMSGFESTAR(I,J)	Real	RMS force estimator function for tips or slides to starboard (g).
RMSGFESTARVEL(I,J)	Real	RMS time derivative of starboard estimator (g/s).
RMSLONGDISP(I,J)	Real	RMS longitudinal displacement (ft or m).
RMSLONGVEL(I,J)	Real	RMS longitudinal velocity (ft/s or m/s).
RMSLONGACC(I,J)	Real	RMS longitudinal acceleration (g).
RMSLONGFE(I,J)	Real	RMS longitudinal force estimator (g).
RMSGFEFORE(I,J)	Real	RMS force estimator function for tips or slides forward (g).
RMSGFEFOREVEL(I,J)	Real	RMS time derivative of forward estimator (g/s).
RMSGFEAFT(I,J)	Real	RMS force estimator function for tips or slides aft (g).

RMSGFEAFTVEL(I,J) Real RMS time derivative of aft estimator (g/s).

Note: The above arrays have dimensions (NSEADIR, NPOS).

Record 27 - Label for RMS Sea Loads in Irregular Waves
Written only if NSTLOAD $\geq$ 1 in Record (6)
Format (A32)

RMSLOADLABEL Ch*32 "RMS Sea Loads in Irregular Waves"

Record 28 - RMS Sea Loads
Written only if NSTLOAD $\geq$ 1 in Record (6)
Format (10(E12.6, 1X))

RMSHORSHR(I,J)	Real	RMS horizontal shear (lb or N).
RMSHORSHRVEL(I,J)	Real	RMS time derivative of horizontal shear (lb/s or N/s).
RMSVERTSHR(I,J)	Real	RMS vertical shear (lb or N).
RMSVERTSHRVEL(I,J)	Real	RMS time derivative of vertical shear (lb/s or N/s).
RMSTORSION(I,J)	Real	RMS torsion (lb·ft or N·m).
RMSTORSIONVEL(I,J)	Real	RMS time derivative of torsion (lb·ft/s or N·m /s).
RMSVERTBND(I,J)	Real	RMS vertical bending moment (lb·ft or N·m).
RMSVERTBNDVEL(I,J)	Real	RMS time derivative of vertical bending moment (lb·ft/s or N·m/s).
RMSHORBND(I,J)	Real	RMS horizontal bending moment (lb·ft or N·m).
RMSHORBNDVEL(I,J)	Real	RMS time derivative of horizontal bending moment (lb·ft/s or N·m/s).

Notes: The above arrays have dimensions (NSEADIR, NSTLOAD).

Annex B
SHIPMO7 Input File for Frigate

```
SHIPMO7 input file of frigate for ship defence models, L = 120 m
METRIC METRIC SALT NOSPEEDCOR NOSWELLCOR MOTION OUTASCII  <- Controls
frigateRao.dat
NOLOAD   NORAW                                  <----- Additional flags
0.2 2.0 0.1                                  <----- Wave frequencies
NOSAVEHY  BOUND2D  LATI NG  HVCOR             <----- Hydrodynamic options
0.2 6.0 0.2                                  <----- Encounter frequencies
BRETSCHNEIDER                                <----- Wave spectrum
13 0.0                                 <----- # of sea dirs, spread angle
0 15 30 45 60 75 90 105 120 135 150 165 180  <----- Sea direction(s)
1                              <----- Number of seaways
3.25 9.7                                <----- Wave height, period
7 0.0 5.0 10.0 15.0 20.0 25.0 30.0  <----- # of ship speeds, speeds
120.0 6.0 30.0                          <- Ship length, KG, pitch gyradius
GMCOMP  DRYROLLRG                       <-- GM and roll gyradius flags
4.8                                     <-- Dry roll radius of gyration
OFFSETS                                 <----- Hull definition flag
21 21 1.0 1.0                           <----- # of stations, scale factors
     0.0
29
 0.000   0.030   0.036   0.048   0.065   0.090   0.122   0.161   0.208
 0.262   0.324   0.394   0.471   0.558   0.654   0.760   0.875   0.997
 1.127   1.264   1.409   1.560   1.718   1.881   2.049   2.300   2.512
 2.725   2.751
 4.427   4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636
 6.912   7.189   7.465   7.742   8.018   8.295   8.571   8.848   9.124
 9.401   9.677   9.954  10.230  10.507  10.783  11.060  11.462  11.793
12.125  12.166
     1.0
30
 0.000   0.169   0.283   0.387   0.485   0.575   0.656   0.728   0.795
 0.862   0.929   0.998   1.066   1.135   1.205   1.275   1.346   1.417
 1.491   1.565   1.641   1.719   1.799   1.884   1.972   2.065   2.163
 2.265   2.371   4.849
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465  11.889
     2.0
30
```

```
 0.000   0.169   0.449   0.693   0.902   1.085   1.250   1.404   1.547
 1.683   1.816   1.944   2.069   2.189   2.304   2.415   2.523   2.630
 2.736   2.840   2.944   3.048   3.153   3.260   3.368   3.478   3.591
 3.707   3.827   5.942
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465  11.613
    3.0
30
 0.000   0.169   0.684   1.073   1.394   1.662   1.896   2.111   2.312
 2.503   2.685   2.861   3.029   3.191   3.345   3.492   3.632   3.767
 3.895   4.019   4.139   4.254   4.367   4.477   4.585   4.692   4.796
 4.900   5.004   6.504
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465  11.336
    4.0
30
 0.000   0.169   1.095   1.637   2.035   2.367   2.653   2.908   3.142
 3.361   3.567   3.762   3.950   4.130   4.302   4.464   4.618   4.760
 4.893   5.017   5.132   5.240   5.341   5.435   5.523   5.607   5.688
 5.767   5.845   6.878
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465  11.060
    5.0
30
 0.000   0.169   1.341   2.094   2.620   3.032   3.376   3.675   3.940
 4.180   4.399   4.601   4.788   4.962   5.123   5.272   5.410   5.537
 5.653   5.759   5.857   5.945   6.027   6.101   6.171   6.236   6.298
 6.357   6.415   7.113
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465  10.783
    6.0
30
 0.000   0.169   1.428   2.435   3.134   3.655   4.061   4.393   4.675
 4.921   5.137   5.329   5.502   5.658   5.800   5.928   6.045   6.151
 6.247   6.334   6.412   6.483   6.545   6.601   6.652   6.699   6.744
 6.788   6.831   7.301
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
```

```
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465  10.507
    7.0
30
 0.000   0.169   1.428   2.646   3.555   4.188   4.658   5.023   5.320
 5.565   5.772   5.948   6.098   6.228   6.339   6.436   6.520   6.595
 6.661   6.721   6.776   6.826   6.872   6.913   6.950   6.984   7.017
 7.050   7.082   7.411
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465  10.230
    8.0
30
 0.000   0.169   1.428   2.687   3.813   4.587   5.120   5.504   5.799
 6.033   6.222   6.376   6.503   6.607   6.692   6.762   6.820   6.870
 6.913   6.951   6.987   7.020   7.052   7.083   7.114   7.145   7.175
 7.204   7.231   7.478
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465   9.954
    9.0
30
 0.000   0.169   1.428   2.687   3.915   4.792   5.416   5.826   6.120
 6.341   6.511   6.644   6.749   6.831   6.895   6.946   6.986   7.021
 7.051   7.080   7.108   7.135   7.162   7.188   7.214   7.239   7.265
 7.291   7.316   7.521
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465   9.677
   10.0
30
 0.000   0.169   1.428   2.687   3.947   4.963   5.568   5.972   6.262
 6.475   6.635   6.758   6.853   6.926   6.981   7.021   7.048   7.072
 7.096   7.120   7.144   7.169   7.193   7.217   7.241   7.265   7.290
 7.314   7.338   7.507
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465   9.401
   11.0
30
```

```
 0.000   0.169   1.428   2.687   3.956   4.930   5.513   5.913   6.207
 6.429   6.598   6.729   6.829   6.905   6.960   7.001   7.033   7.060
 7.086   7.115   7.144   7.168   7.193   7.217   7.241   7.265   7.290
 7.314   7.338   7.507
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465   9.401
    12.0
30
 0.000   0.169   1.428   2.677   3.833   4.758   5.372   5.797   6.107
 6.340   6.519   6.656   6.761   6.842   6.905   6.954   6.994   7.028
 7.058   7.087   7.116   7.143   7.170   7.198   7.229   7.259   7.288
 7.314   7.338   7.507
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465   9.401
    13.0
30
 0.000   0.169   1.383   2.554   3.624   4.500   5.129   5.582   5.920
 6.177   6.376   6.532   6.652   6.746   6.820   6.878   6.923   6.960
 6.993   7.024   7.056   7.086   7.115   7.143   7.169   7.193   7.218
 7.242   7.266   7.437
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465   9.401
    14.0
30
 0.000   0.169   1.314   2.364   3.311   4.126   4.745   5.228   5.605
 5.903   6.139   6.326   6.472   6.587   6.677   6.748   6.803   6.849
 6.888   6.924   6.957   6.988   7.015   7.041   7.066   7.092   7.117
 7.142   7.168   7.345
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465   9.401
    15.0
30
 0.000   0.169   0.899   1.804   2.682   3.503   4.186   4.721   5.147
 5.494   5.776   6.005   6.189   6.337   6.456   6.551   6.628   6.690
 6.742   6.784   6.819   6.849   6.876   6.902   6.928   6.954   6.980
 7.006   7.032   7.214
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
```

```
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465   9.401
    16.0
30
 0.000   0.169   0.169   0.632   1.501   2.359   3.180   3.892   4.473
 4.931   5.295   5.588   5.827   6.021   6.177   6.301   6.400   6.478
 6.540   6.591   6.631   6.663   6.690   6.718   6.745   6.773   6.800
 6.828   6.856   7.049
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465   9.401
    17.0
30
 0.000   0.000   0.169   0.169   0.169   0.169   0.793   1.949   2.939
 3.804   4.465   4.955   5.322   5.603   5.819   5.988   6.122   6.229
 6.313   6.379   6.430   6.472   6.505   6.534   6.564   6.593   6.622
 6.651   6.680   6.884
 0.000   0.000   0.276   0.553   0.829   1.106   1.382   1.659   1.935
 2.212   2.488   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465   9.401
    18.0
27
 0.000   0.169   2.575   3.945   4.684   5.173   5.521   5.771   5.949
 6.073   6.153   6.206   6.246   6.280   6.313   6.346   6.379   6.412
 6.446   6.479   6.512   6.545   6.578   6.611   6.645   6.678   6.711
 2.499   2.499   2.765   3.041   3.318   3.594   3.871   4.147   4.424
 4.700   4.977   5.253   5.530   5.806   6.083   6.359   6.636   6.912
 7.189   7.465   7.742   8.018   8.295   8.571   8.848   9.124   9.401
    19.0
23
 0.000   0.406   4.924   5.410   5.643   5.775   5.846   5.890   5.931
 5.972   6.013   6.055   6.096   6.137   6.178   6.219   6.260   6.302
 6.343   6.384   6.425   6.466   6.507
 3.611   3.611   3.871   4.147   4.424   4.700   4.977   5.253   5.530
 5.806   6.083   6.359   6.636   6.912   7.189   7.465   7.742   8.018
 8.295   8.571   8.848   9.124   9.401
    20.0
23
 0.000   4.181   4.194   5.041   5.300   5.413   5.473   5.530   5.586
 5.640   5.692   5.744   5.795   5.846   5.896   5.947   5.998   6.049
 6.101   6.151   6.201   6.251   6.302
 3.870   3.870   3.871   4.147   4.424   4.700   4.977   5.253   5.530
```

```
 5.806   6.083   6.359   6.636   6.912   7.189   7.465   7.742   8.018
 8.295   8.571   8.848   9.124   9.401
DRAFT              <----- Control flag for load waterline
4.2 0.0            <----- Draft, trim
0 20.0 0.01        <----- Seakeeping position data
1                  <----- Number of bilge keel pairs
6  14              <----- First and last stations spanned by bilge keel
 6.0  6.5  5.14    2.49  0.60     <----- Bilge keel data
 6.5  7.5  5.57    2.21  0.60
 7.5  8.5  5.80    1.94  0.60
 8.5  9.5  5.83    1.66  0.60
 9.5 10.5  5.97    1.66  0.60
10.5 11.5  5.91    1.66  0.60
11.5 12.5  5.80    1.66  0.60
12.5 13.5  5.58    1.66  0.60
13.5 14.0  5.23    1.66  0.60
16.0  1.2  12.0                    <----- Skeg
19.0 0.0 3.6 4.8 4.8 2.4 0.0 0     <----- Rudder data
0.0 0.0 0.0 0.0 0.0 0.0 0.0        <----- Rudder roll gains
0.0 0.0 0.0                        <----- Rudder yaw gains
0                          <----- Number of stationary foil pairs
NOSTAB                             <----- Fin or tank stabilization
```

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3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C,R or U) in parentheses after the title.)
Efficient Predictions of Wave-Induced Ship Motions for Ship Defence Models

4. AUTHORS (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)
McTaggart, Kevin A.

5. DATE OF PUBLICATION (month and year of publication of document)	6a. NO. OF PAGES (total including Annexes, Appendices, etc).	6b. NO. OF REFS (total cited in document)
February 2004	48	17

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final.)
Technical Memorandum

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include address).
Canadian Forces Maritime Warfare Centre, P.O. Box 99000 STN Forces, Halifax, Nova Scotia, B3K 5X5

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written.)	9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written).
11GK12	

10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique.)	10b. OTHER DOCUMENT NOs. (Any other numbers which may be assigned this document either by the originator or by the sponsor.)
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This report presents a library of wave-induced ship motion modules for use in simulation applications. The library is intended for ship defence models and other simulation applications requiring robustness, fidelity, and high computational speed. Ship motions in long-crested random seaways are determined using ship motion response amplitude operators (RAOs) computed by DRDC Atlantic's SHIPMO7 program. The output ship motions are given as perturbations relative to the steady or slowly varying input ship course. Time domain predictions from the library have been verified through comparisons with frequency domain predictions from SHIPMO7, which has undergone extensive validation. The library is available as a Python module and also as a dynamically linked library (DLL) callable from C++ and other compiled languages. During benchmarking on a 800 MHz Pentium III computer, ship motion predictions required approximately 0.002 s per time step, giving performance 50 times faster than real time for a typical simulation application using a time step size of 0.1 s.

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heave
pitch
ocean waves
roll
seakeeping
ship motions
simulation
surge
sway
yaw